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The Use of Location and Location-Intensity Patterns in Electrocutaneous Communication

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Part I

Formulation of the Problem

Objectives

The aim of the research described in this report has been to develop and test electrocutaneous codes for general language communication and, in the process, to investigate further man's information handling abilities. Also, the electrocutaneous stimulus itself has been studied in the belief that a better understanding of its basic properties might facilitate the construction of more efficient electrocutaneous codes.

The major objective has been the development of an electrocutaneous code for the communication of general language information at useful rates. This objective involves both practical and theoretical considerations. It has practical implications because the development of such a code might serve well in solving certain current problems in communication. For example, there are many situations in which visual and auditory channels are either overloaded with ongoing communication or rendered nearly useless by interferring noise. In situations such as these, the transmission of general language information might be accomplished better through use of another sensory channel. The cutaneous channel is an obvious candidate for this use. It is presently unused for the most part, it is responsive to stimulation of known sorts, and it is fairly well protected from extraneous stimulation. In addition, electrical stimulation of the skin seems to offer an ideal signal source for those situations in which private communication is required. The signal is invisible and inaudible, and it can be made both effective and flexible. Unlike the visual or auditory stimulus, the electrical signal must be applied directly to the person of the intended receiver and this further insures the privacy of communication.

The objective has theoretical implications because the process of developing a code will permit validation of findings regarding the legibility of electrocutaneous stimulus alphabets, the characteristics of response alphabets for language information, and the compatibility effect of stimulus-response ensembles. As matters presently stand, further advances in these three areas demand a full scale test of the predictions and implications of the current generalizations. Such a test was sought in the construction of the general purpose electrocutaneous communication language reported herein.

Background

Legibility of the Stimulus Alphabet

One decision that must be made before constructing a cutaneous code is that of the number of dimensions to be employed in the signals that make up the code. Fortunately, there are relevant data that proved useful in making this decision.

A three dimensional vibrotactile code, in which the stimulus was varied in location, intensity, and duration, was studied by Howell (1956). Communication was clearly demonstrated, but not without a large number of confusions involving the dimensions of intensity and duration. Using a similar approach, Foulke (1964, 1965a) trained Ss in the use of a three dimensional electrocutaneous code. Communication rates of over 20 words per minute (wpm) with unfamiliar prose were achieved. However, as in the case of the vibrotactile code, confusions of intensity and duration were numerous and persistent. Furthermore, response times to the code signals were distressingly long and it appeared that the tridimensional code signals were not readily subitized, even after many months of training.

The informal experience of those associated with the electrocutaneous code project at the University of Louisville lead to the hypothesis that the communication rate possible with use of a cutaneous code is an inverse function of the number of stimulus dimensions employed in composing code signals. This hypothesis was evaluated experimentally (Foulke, Alluisi & Coates, 1966). A different electrocutaneous code was taught to each of four experimental groups. Group 1 learned a code based on location cues alone. Group 2 learned a code using location and intensity as cues. Group 3 learned a code with location and duration cues, and Group 4 learned a code with all three cues, location, intensity and duration. The results showed Codes 1 and 2 to be best in terms of communication rate. Code 3 was intermediate and Code 4 was poorest.

In the location code evaluated in this experiment, only one location was stimulated at a time. If a code with a large number of signals were constructed in this way, the person receiving the signals would be required to make a large number of absolute identifications within the single stimulus dimension of location. This may be possible, but there is little evidence regarding man's ability to do so. Experimental results regarding the number of absolute identifications available in other electrocutaneous stimulus dimensions indicate that the number is too small for any but the simplest of codes, if only one value in a stimulus dimension is to be presented at a time. For instance, Hawkes (1960, 1961) and Hawkes and Warm (1960) obtained three absolute stimulus identifications in the intensity dimension and Hawkes (1961a, 1961b) obtained four absolute stimulus identifications in the duration dimension.

One solution to this problem is the simultaneous presentation of stimuli at more than one location. Croner (1960) has discussed the problem of acuity when electrical stimuli are applied in this manner, and Alluisi, Morgan and Hawkes studied the effects of acuity for numerosity. When more locations than two are stimulated at one time, the S sometimes fails to report stimulation at one or more of the locations. There appears to be some central mechanism of cutaneous masking for this occurs even when the signals are widely separated on the skin (Alluisi, Morgan and Hawkes, 1965).

Additional research at the University of Louisville has indicated that, with relatively little practice, Ss can name patterns composed of two stimulated locations with good accuracy when the two are on different sides of the body. They can also identify patterns composed of three stimulated locations, two on one side of the body and one on the other, well enough to suggest further consideration of this approach in coding the electrical stimulus.

Further support of this conclusion has been obtained by Foulke, Morgan and Alluisi (Foulke, 1965), with tests of a location pattern code in which six fingertips, three on each hand, could be stimulated. The stimulus was a brief dc pulse. The patterns used were the same as those that occur in the Braille Code, which makes use of six dot locations. The S was an experienced braille reader and he responded to patterns of dc stimuli by pronouncing the letter associated with the dot pattern in the Braille Code that resembled the dc stimulus pattern. This arrangement resulted in a code with relatively high stimulus-response compatibility for the S in question. The S's task was merely to substitute patterns of electrical stimuli for patterns of the over-learned braille stimuli. When all possible combinations within six possible locations were used, the S responded with less than 20% error. The patterns most frequently involved in error were those containing more than three locations on a single hand. The S was tested on a code in which these patterns were eliminated and he performed with fewer than five percent errors. This "optimized" code contained 39 signals, a number sufficient for the construction of a simple alphanumeric code. More sophisticated codes would require larger numbers of signals, of course. In order to investigate the possibility of using such codes, a study was undertaken by Foulke, Morgan & Alluisi (Foulke, 1965), for the purpose of comparing three location-pattern codes that differed with respect to the number of possible locations available for forming stimulus patterns. The first code made use of six locations, three fingertips on each hand. An eight location code made use of four fingertips on each hand, and a ten location code made use of all five fingertips on each hand. Only those patterns formed from three or fewer locations were used, and patterns involving all three locations on a single hand were also discarded. Each code contained 39 signals, and the three codes were balanced with respect to the number of 1-location, 2-location and 3-location patterns. Comparison of the errors made by the three groups of Ss who learned these codes showed them to be fairly equal in difficulty. Differences were small and of no practical significance. On the strength of these results, two more codes were compared, an eight and a ten location code, each containing 39 signals. However, these codes were optimized by using all possible one and two location patterns and only as many three location patterns as were needed to make up the required number of 39 code signals. Under these conditions, fewer errors were made by those who learned the ten location code.

Response Alphabet

So far, the efforts to communicate by stimulation of the skin has made use of simple or slightly modified literal codes. For instance, the Braille Code, which uses patterns of punctiform stimuli, has a response alphabet containing sixty three characters, letters, punctuation marks, and frequently recurring letter groups such as "and", "ing" and "etc.", and abbreviations for common short words. The vibrotactile code evaluated by Howell contained 45 characters consisting of letters, numbers, and a few words; for example, the articles "the", "and", and "an". Finally, the three dimensional electrocutaneous code evaluated by Foulke employed a 39 element response alphabet consisting of letters, numbers, punctuation marks, and a few of the contractions that occur in the Braille Code.

Though contractions and abbreviations may be helpful, codes of the sort just mentioned still require the receiver to identify a relatively large number of code elements for most words received. Conventional, written language is communicated visually by means of a simple, uncontracted alphanumeric code. However, the visual span is large enough so that whole words or groups of words may be perceived simultaneously or very nearly so. The reader learns to recognize whole or part word shapes so that he is relieved of the necessity of constructing words from successions of separately perceived letters. This ability of the visual reader to convert the literal code into a code with perceptual units that carry much more information than is carried by a single letter results, of course, in a greatly increased rate of communication. In the case of electrocutaneous codes like the one studied in this report, code elements must be presented to the S one at a time and therefore must be perceived successively. Piecemeal presentation means piecemeal perception. If a literal cutaneous code is used, such as one based on English letters, this limitation results in a relatively slow communication rate. This is also the case with auditory signals, such as those used in Morse Code. Although man receives language information aurally, that is, from hearing speech, at rates of 100 to 300 wpm, the expert military standard for Morse Code reception is 24 wpm. Morse Code is based on sending letters whereas speech is based upon some other perceptual unit.

One kind of solution to this problem has been the modification of the response alphabet. The use of contractions and abbreviations in the Braille Code affords a good example. However, such solutions have been only modifications. The basic literal alphabet has been retained. A more radical solution was proposed by Alluisi (1961). He suggested the pairing of elements in the stimulus alphabet of a cutaneous code with the response elements of a language syllabary. To test this notion, he suggested the coding of the Japanese Katakana Syllabary. The use of Katakana with Japanese speakers should result in a fairly rapid test of the feasibility of this approach toward the coding of the electrocutaneous stimulus. Japanese students are trained, in the primary grades, to use Katakana. They, unlike naive Ss, would have only the stimulus alphabet of electrocutaneous signals to learn. In accordance with this line of reasoning, Japanese individuals have been employed as Ss in the work reported here (see Part II, p. 23), and have learned a code in which patterns of electrical stimuli have been paired with the elements in the Katakana Syllabary.

Stimulus-Response Compatibility

One of the factors determining the facility with which an association between a stimulus and a response can be formed is their compatibility. This factor is of crucial significance in choosing the elements in a response alphabet that are to be paired with the elements in an electrocutaneous stimulus alphabet. The question of compatibility has been discussed by several writers, and it was taken into account in making stimulus-response assignments in the codes constructed here (see Part II, p. 14). It has been pointed out (Alluisi, 1961) that the 26 letters of the English alphabet are poorly suited for the immediate perception of language in any form except that of reading the printed word. Likewise, phonemes appear to be poorly suited as response elements of an electrocutaneous communication system. Aside from their unfamilarity to the general population, individual phonemes are not ordinarily perceived by listeners when they hear speech any more than the individual letters are perceived when reading. Some combined literate-linguistic form may prove to be the most compatible response alphabet for these purposes, a set of forms that would have the familarity of letters to combine with the implicit perceptability of speech. A syllabic alphabet may fulfil these requirements. The use of Japanese speakers and the Japanese language to test this reasoning fulfills both practical and theoretical purposes. The test has the practical advantage of providing an estimate of the information handling rate obtainable with what has been predicted to be a highly compatible ensemble and it provides this with minimum training time. Secondly, the test should indicate the desirability of continuing along these lines in the development of a suitable syllabic alphabet for use with English and other Western European languages. Obviously, if the gain is not large relative to what can be realized with letters alone, further work on the compatibility of these stimulus and response alphabets is not warranted. On the other hand, if the test produces receiving rates nearly equivalent to those for speech or reading, further development of a code for use with English language is warranted.

Part II

The Construction and Evaluation of Four Katakana Codes

Determination of Feasible Locations for Use in a Location Pattern Code

In the encoding scheme employed in this project, the representation of the elements in the Japanese Katakana Syllabary by electrocutaneous code signals requires the use of patterns formed from 1, 2, or 3 stimulated fingertip and palm locations. Although previous work (See Part 1, p. 3) had indicated the feasibility of such patterns, it was decided to conduct a pilot study to check more specifically upon the kind of patterns that would actually be employed in the codes to be tested. Accordingly, a group of signals was tested that included patterns composed of only one location, patterns composed of two locations on a single hand, and patterns with three locations, two on one hand and one on the other. The test consisted of requiring Ss to identify the stimulated location or locations that constituted the stimulus patterns.

Method

Apparatus

The stimuli from which signals were composed were dc pulses produced by the sudden voltage rise that occurs when the current flowing in an inductive circuit is interrupted. One side of the 6.3 volt winding of a small filament transformer was connected to the negative terminal of a 1.5 volt battery. The positive terminal of the battery was returned through the normally closed contacts of a single pole double throw momentary switch to the other side of the 6.3 volt winding. One side of the 117 volt winding was connected to S's active electrode. His passive electrode was connected through a rheostat to the other side of the 117 volt winding. When the switch in the low voltage winding was operated, a pulse was produced with a nearly instantaneous onset, an exponential offset, and a duration of approximately .5 milliseconds (msec.). The intensity of this pulse could be adjusted by means of the rheostat. Separate circuits, sharing a common return, were provided for each of the locations under test. The switches, which were ordinary micro-switches, were bolted together to form a keyboard. From this keyboard, patterns of pulses could be delivered to S's fingertips and palms by pressing the appropriate combinations of keys.

The active electrodes were stainless steel discs, 14 millimeters in diameter, and were mounted on handboards in such a way that when S's hands were properly positioned on these boards, the electrodes contacted the appropriate locations. The positions of the electrodes on each handboard could be adjusted slightly to make allowances for differences in hand sizes. Two passive electrodes were provided, one on the ventral surface of each wrist. Limb electrodes of the sort found in EKG apparatus were used for this purpose. No electrode paste was used.

Procedure

Before testing commenced, each S adjusted stimulus intensity for comfort, and for equal apparent intensity at all the locations under test. He was also acquainted with a simple response alphabet to be used in describing stimulus patterns that consisted of a numbering scheme for the locations employed in the study. During the test, random sequences of stimulus patterns were presented to S. He identified them by pronouncing the numbers corresponding to the locations used in forming patterns.

Results

The stimulus patterns that were tested are shown in Figure 2.1. In the first test (see Figure 2.1B), 11 patterns involving 7 stimulus locations were examined. Seven of these were 1-location patterns in which the 5 fingertips and locations at the base of the little finger and the base of the hand were stimulated singly. The remaining patterns were 2-location patterns formed

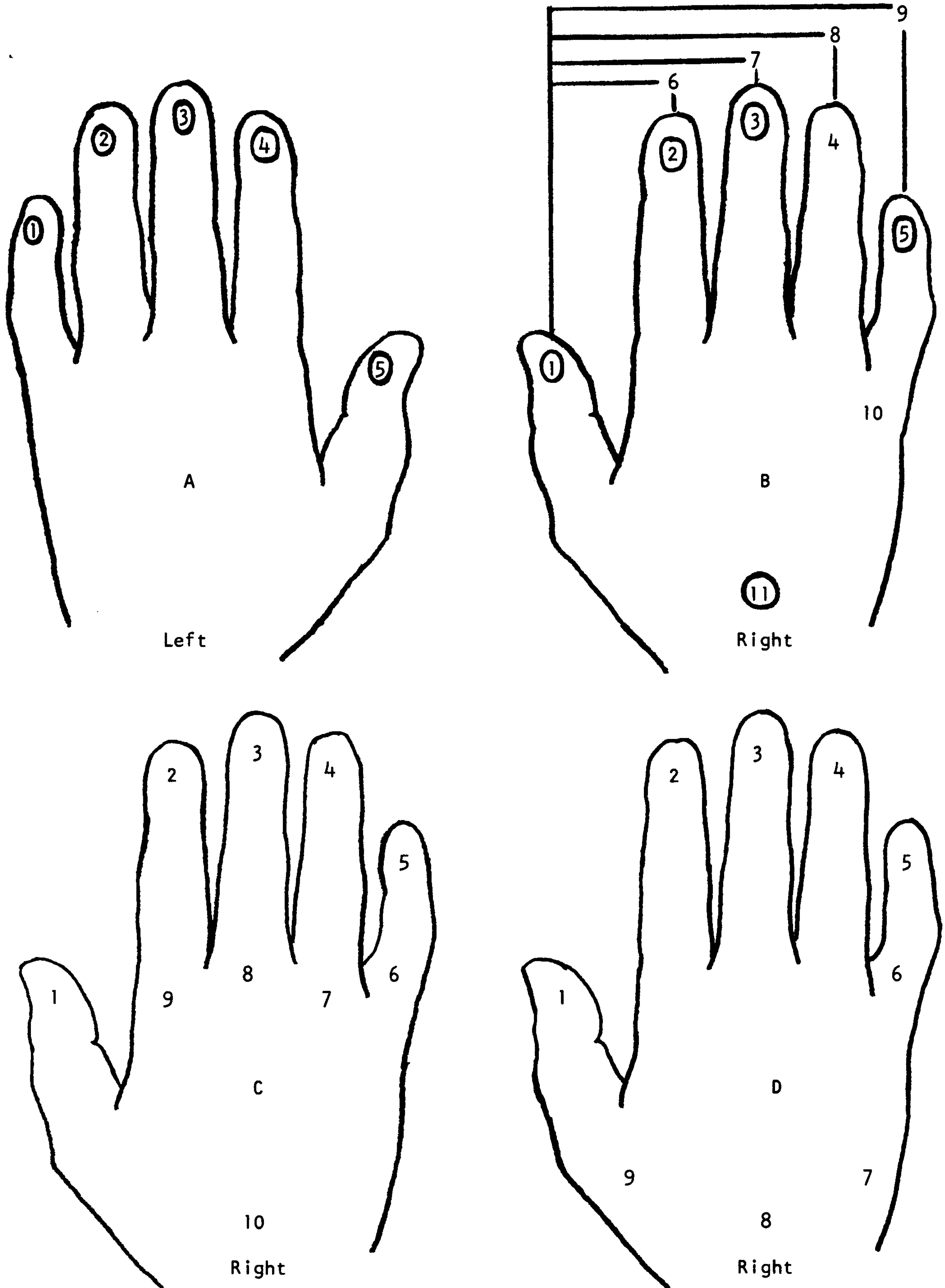

Figure 2.1 Locations tested using 1 & 2 points on the right hand (B, C, D) and 2-points on the right hand coupled with 1-point on the left hand (the circled locations on A & B).

by pairing the thumb tip with the four fingers. Two project members, with considerable experience in responding to electrical stimulation of the skin, served as _S_s. Each _S_ made 24 observations of each of the 11 patterns. Thus, each _S_ made 264 observations, and there were 528 observations in all. Five hundred and fourteen, or 97% of the observations resulted in correct pattern identifications. There were 336 observations of 1-location patterns. Three hundred and thirty five, or 99.7% of these observations resulted in correct pattern identifications. There were 192 observations of 2-location patterns. Of these, 179, or 93%, were correctly identified.

In the second test, 14 patterns involving 10 locations were evaluated (see Figure 2.1C). Ten of these were 1-location patterns. The other 4 were 2-location patterns, formed by pairing location 10, the location at the base of the hand, with the thumb, first, second or little fingertips. Each of the two _S_s made 20 observations of each of the 14 patterns. Thus, there were 280 observations per _S_, and 560 observations in all. Five hundred and thirty, or 95% of the observations resulted in correct pattern identification. There were 400 observations of 1-location patterns. Three hundred and seventy-six, or 94% of these observations were correct identifications. There were 160 observations of 2-location patterns. One hundred and fifty-four, or 96% of these observations resulted in correct identifications.

Two conclusions are suggested by the comparison of the results of Test 1 with those of Test 2.

a. With respect to 1-location patterns, fingertip locations can be more accurately identified than locations elsewhere on the hand. In Test 1, 99.7% of the 1-location patterns presented were identified correctly. Five out of 7 of these patterns involved fingertip locations. In the second test, only 94% of the 1-location patterns were correctly identified. In this case, 5 of the 10 1-location patterns involved palmer locations.

b. Two-location patterns can be identified more accurately when the locations that make up the pattern are well separated. In Test 1, 93% of the 2-location patterns were identified correctly. In all of these patterns, the thumb was paired with one of the remaining fingertips. In Test 2, 96% of the 2-location patterns were identified correctly. In this case, the location paired with each of the fingertip locations was always at the base of the hand, resulting in a greater separation of stimulated locations in each pattern.

In Test 3, 9 1-location patterns were evaluated (see Figure 2.1D). Each of the two Ss made 24 observations of each of the 9 patterns. Thus, each S made 216 observations, and there were 432 observations in all. Of these, 412, or 95% resulted in correct pattern identifications. There were 240 observations of the 5 patterns involving only fingertip stimulation, and no errors were made. There were 192 observations of the 4 patterns involving stimulation at locations other than the fingertips. Of these observations, 172 resulted in correct pattern identifications.

The results of Test 3 may be taken as confirmation of the impression conveyed by the preceeding tests. One-location patterns involving fingertip locations, are clearly more legible than similar patterns presented at other locations. Nevertheless, legibility of 1-location patterns involving other than fingertip locations may be high enough to warrant their use on those occasions when the use of fingertip locations only will not meet the signal requirement for the code under construction.

In Test 4, patterns formed from 3 stimulated locations were evaluated. Each pattern was composed of two locations on the right hand, (location 10 at the base of the hand plus either the thumb, first, second or little fingertips) and one location on the left hand (any one of the five fingertips). These locations are indicated by the circled positions in Figure 2.1A and B. This arrangement permitted the formation of 20 different patterns. One S made 10 observations of each stimulus pattern for a total of 200 observations. A second S made 5 observations of each stimulus pattern for a total of 100 observations. Combining the data for the two Ss gave 300 observations, of which 270,or 90% were correct identifications.

In effect, the 2-location patterns in Test 2 were changed to the 3-location patterns in Test 4 by the addition of a third, left fingertip location, to each of the patterns. Adding this third location reduced accuracy of identification from 96% to 90%.

In summary, it appears that 1-location patterns yield the highest accuracy of identification, and that fingertip locations are to be preferred to locations elsewhere on the fingers or palms. If patterns composed of two locations on a single hand are to be employed, wide separation of those locations results in somewhat better pattern identification. Members of a 3-location set of patterns that have been generated by adding a left hand location to each of the members of the best set of 2-location patterns are identified less accurately than the members of the set from which they were generated. However, accuracy of identification of these patterns is still high enough to warrant their use when other, more identifiable patterns are not available.

Encoding the Katakana Syllabary

Using the information reported in the preceding paragraphs, each of the symbols in the Katakana alphabet was paired with an electrocutaneous signal that consisted of a pattern of simultaneously stimulated locations. Since all of the patterns tested were reasonably legible, additional factors were also taken into account in making assignments. A conventional spatial arrangement is employed to display the symbols in the Katakana Syllabary (see Table 2.1). This syllabary is conventionally read (or recited) by columns, proceeding from right to left and each column is read from top to bottom. Since Japanese people, thoroughly schooled in these conventions, were to learn the code, an effort was

TABLE 2.1

The Katakana Syllabary

5	4	3	2	1
HA (PA) (BA)	TA (DA)	SA (ZA)	KA	(GA)* A
HI (PI) (BI)	TI (DI)	SI (ZI)	KI	(GI) I
HU (PU) (BU)	TU (DU)	SU (ZU)	KU	(GU) U
HE (PE) (BE)	TE (DE)	SE (ZE)	KE	(GE) E
HO (PO) (BO)	TO (DO)	SO (ZO)	KO	(GO) O

10	9	8	7	6
WN	WA	LA	YA	MA
	I	LI	YI	MI
	U	LU	YU	MU
	E	LE	YE	ME
	O	LO	YO	MO

*Symbols in parentheses are alternate sounds for the symbols in the comumn following (reading right to left) the parentheses.

made, where possible, to observe these conventions in assigning code signals to Katakana symbols. It was felt that the code's stimulus-response compatibility might be maximized by basing the rationale for pairing symbols with signals, at least to some degree, upon the conventional arrangement of the Katakana Syllabary.

In consultation with Mr. Hiroshi Tanamachi, a native Japanese who is employed as a research assistant on this project, a variety of schemes for encoding the Katakana Syllabary were considered. There appeared to be no appropriate basis for strongly preferring any one of them. Consequently, a decision was made to test what we believed to be the four most promising codes by teaching them to Japanese Ss, and then, by comparing their performance on the four codes, to determine the best code.

Figure 2.2 shows the locations used in forming the stimulus patterns in all four codes. The four codes are presented in Tables 2.2 through 2.5. In these tables, "R" equals right hand, "L" equals left hand, while the numbers designate the locations to which stimuli were applied, as shown in Figure 2.2. To illustrate, in Code 3, (see Table 2.4) the entry R1 adjacent to the Katakana Symbol A (pronounced like the "a" in father) signifies that when a single pulse to the tip of the right little finger is experienced it is to be interpreted as "A". Similarly, the entry L5-R1 adjacent to the Katakana Symbol "ka" signifies that when pulses are felt simultaneously at the tips of the left thumb and the right little finger, the experience is to be interpreted as "ka".

Comparative Evaluation of the Four Codes

The objective in this phase of the project was to train Japanese Ss to receive the four codes, and to compare their performance on relevant acquisition measures. It was felt that the resulting information would provide a suitable basis either for eliminating all but the best of the four codes, or, in the event that none of the codes seemed promising, for the construction of a new final code.

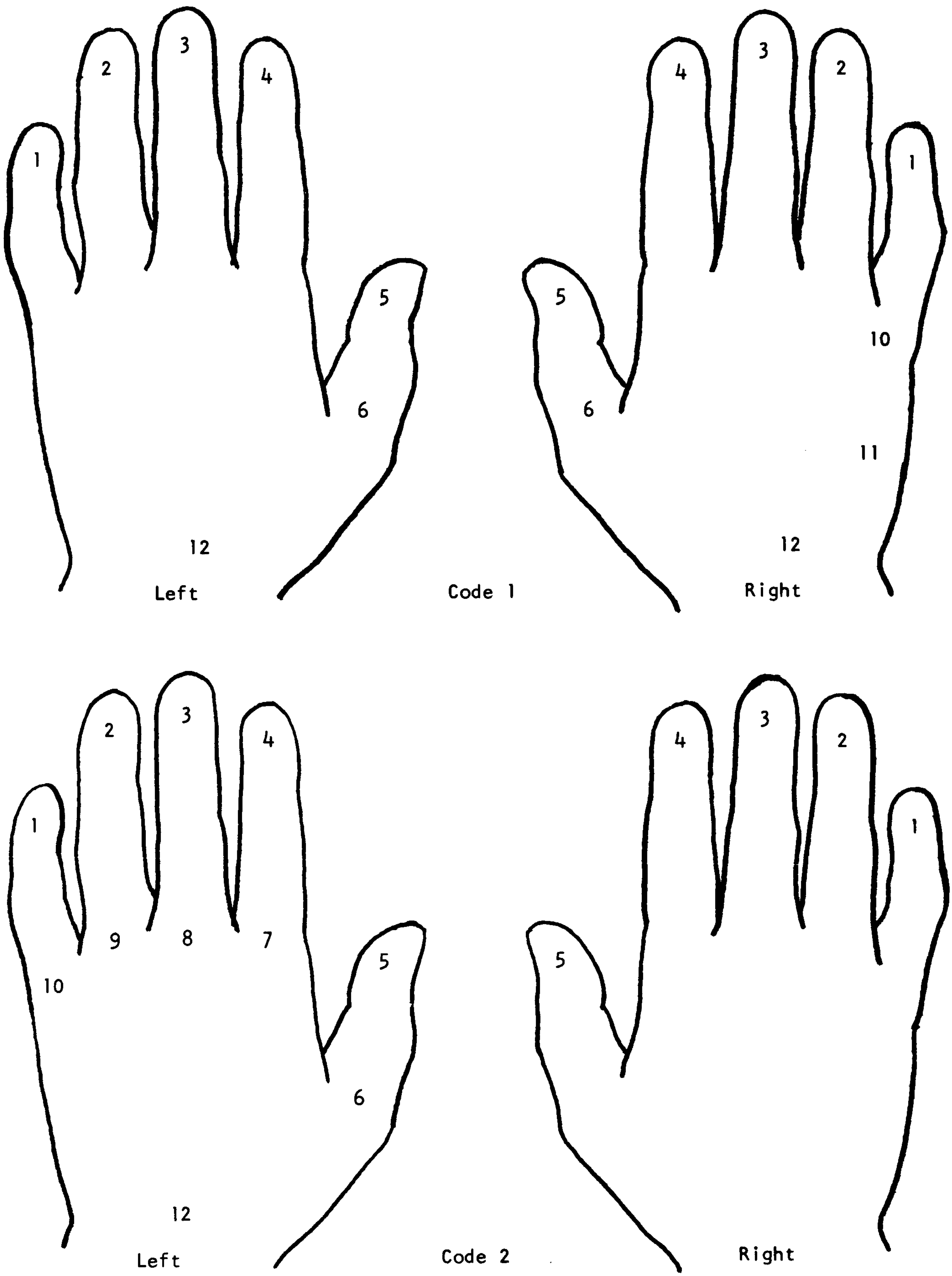

Figure 2.2

Stimulus locations used for each of the Katakana codes.

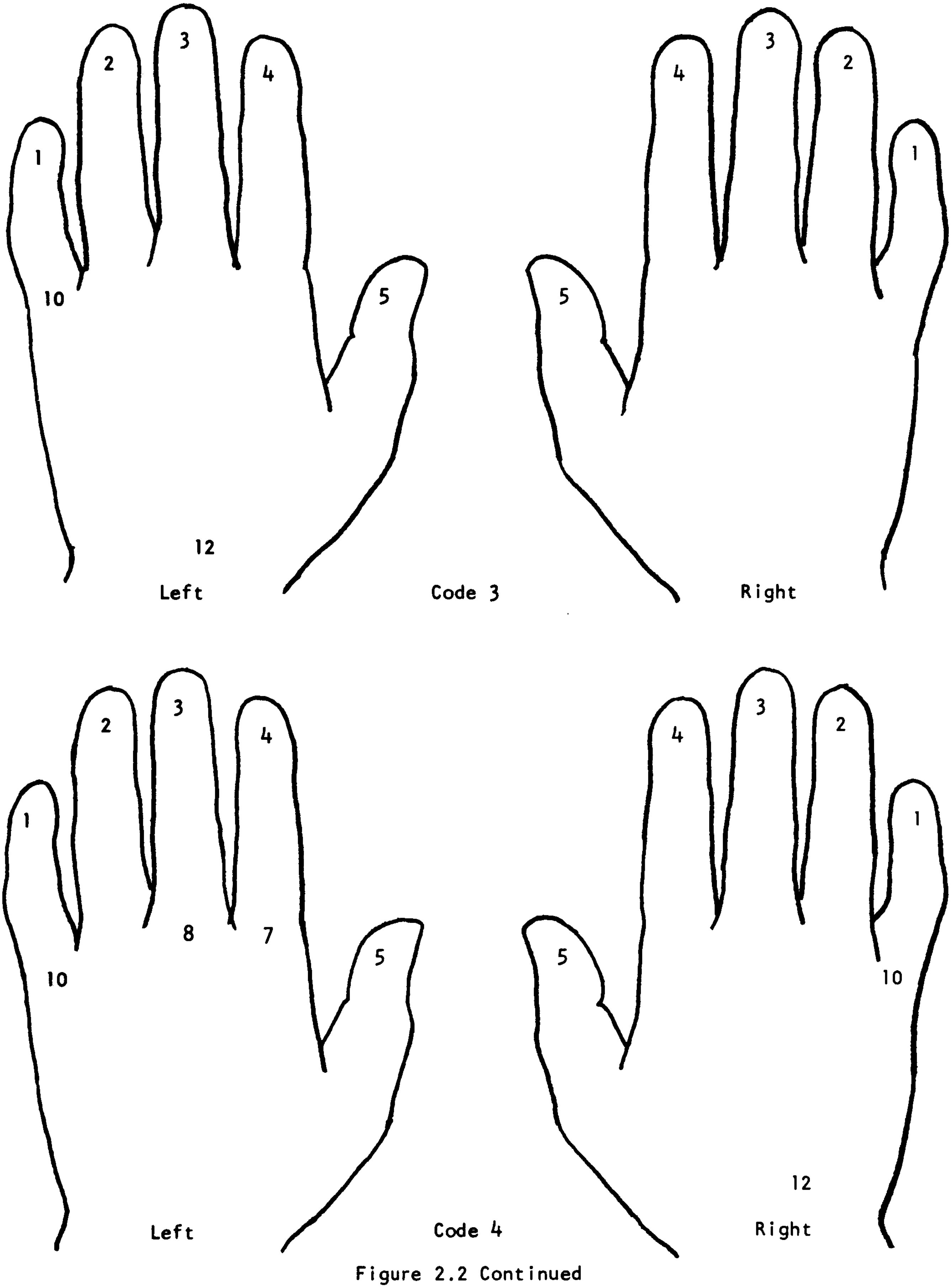

Figure 2.2 Continued

Stimulus locations used for each of the Katakana codes.

TABLE 2.2

Electrocutaneous Katakana Syllabary

CODE #1

A	R1	
*I	R10	
*U	R11	
*E	R12	
*O	R6	
KA	R2-1	
KI	R2-10	
KU	R2-11	
KE	R2-12	
KO	R2-6	
SA	R3-1	
SI	R3-10	
SU	R3-11	
SE	R3-12	
SO	R3-6	
TA	R4-1	
TI	R4-10	
TU	R4-11	
TE	R4-12	
TO	R4-6	
NA	R5-1	
NL	R5-10	
NU	R5-11	
NE	R5-12	
NO	R5-6	
HA	L5R1	
HI	L5R10	
HU	L5R11	
HE	L5R12	

MA	L4R1	
MI	L4R10	
MU	L4R11	
ME	L4R12	
MO	L4R6	
YA	L3R1	
*I	R10	
YU	L3R11	
*E	R12	
YO	L3R6	
LA	L2R1	
LI	L2R10	
LU	L2R11	
LE	L2R12	
LO	L2R6	
WA	L1R1	
*I	R10	
*U	R11	
*E	R12	
*O	R6	
WN	L1	
GA	L12	R2-1
GI	L12	R2-10
GU	L12	R2-11
GE	L12	R2-12
GO	L12	R2-6
ZA	L12	R1-3
*(DI)ZI	L12	R3-10
*(DU)ZU	L12	

DA	L12	R4-1
*(ZI)DI	L12	R4-10
*(ZU)DU	L12	R4-11
DE	L12	R4-12
DO	L12	R4-6
BA	L12-5R1	
BI	L12-5R10	
BU	L12-5R11	
BE	L12-5R12	
BO	L12-5R6	
PA	L6	R1
PI	L5	R10
PU	L6	R11
PE	L6	R12
PO	L6	R6
.	L5	
.	L4	
1	L3	
<	L2	

* Also appears elsewhere

TABLE 2.3

Electrocutaneous Katakana Syllabary

CODE #2

A	R1	MA	L6 R1	DA	L12-3R1
*I	R2	MI	L6 R2	*DI	L12-3R2
*U	R3	MU	L6 R3	(ZU)*DU	L12-3R3
*E	R4	ME	L6 R4	DE	L12-3R4
*O	R5	MO	L6 R5	DO	L12-3R5
KA	L5R1	YA	L7 R1	BA	L12-1R1
KI	L5R2	*I	R2	BI	L12-1R2
KU	L5R3	YU	L7 R3	BU	L12-1R3
KE	L5R4	*E	R4	BE	L12-1R4
KO	L5R5	YO	L7 R5	BO	L12-1R5
SA	L4R1	LA	L8 R1	PA	L10 R1
SI	L4R2	LI	L8 R2	PI	L10 R2
SU	L4R3	LU	L8 R3	PU	L10 R3
SE	L4R4	LE	L8 R4	PE	L10 R4
SO	L4R5	LO	L8 R5	PO	L10 R5
TA	L3R1	WA	L9 R1		
(CHI)TI	L3R2	*I	R2	.	L 5
(TSU)TU	L3R3	*U	R3	,	L 4
TE	L3R4	*E	R4	!	L 3
TO	L3R5	*O	R5	<	L 2
NA	L2R1	WN	L9		
NI	L2R2	GA	L12-5R1		
NU	L2R3	GI	L12-5R2		
NE	L2R4	GU	L12-5R3		
NO	L2R5	GE	L12-5R4		
HA	L1R1	GO	L12-5R5		
HI	L1R2	ZA	L12-4R1		
HU	L1R3	(DI)*ZI	L12-4R2		
HE	L1R4	(DU)*ZU	L12-4R3		
HO	L1R5	ZE	L12-4R4		
		ZO	L12-4R5		

*Also appears elsewhere

TABLE 2.4

Electrocutaneous Katakana Syllabary

CODE #3

A	R1	MA	L4-5R1	DA	L12-3R1
*I	R2	MI	L4-5R2	(ZI)*DI	L12-3R2
*U	R3	MU	L4-5R3	(ZU)*DU	L12-3R3
*E	R4	ME	L4-5R4	DE	L12-3R4
*O	R5	MO	L4-5R5	DO	L12-3R5
KA	L5R1	YA	L3-5R1	BA	L12-1R1
KI	L5R2	*I	R2	BI	L12-1R2
KU	L5R3	YU	L3-5R3	BU	L12-1R3
KE	L5R4	*E	R4	BE	L12-1R4
KO	L5R5	YO	L3-5R5	BO	L12-1R5
SA	L4R1	LA	L2-5R1		
SI	L4R2	LI	L2-5R2	BA	L10 R1
SU	L4R3	LU	L2-5R3	PI	L10 R2
SE	L4R4	LE	L2-5R4	PU	L10 R3
SO	L4R5	LO	L2-5R5	PE	L10 R4
TA	L3R1	WA	L1-5R1	PO	L10 R5
(CHI)TI	L3R2	*I	R2		
TU	L3R3	*U	R3	.	L 5
TE	L3R4	*E	R4	,	L 4
TO	L3R5	*O	R5	1	L 3
NA	L2R1	WN	R12	<	L 2
NI	L2R2	GA	L12-5R1		
NU	L2R3	GI	L12-5R2		
NE	L2R4	GU	L12-5R3		
NO	L2R5	GE	L12-5R4		
HA	L1R1	GO	L12-5R5		
HI	L1R2	ZA	L12-4R1		
HU	L1R3	(DI)*ZI	L12-4R2		
HE	L1R4	(DU)*ZU	L12-4R3		
HO	L1R5	ZE	L12-4R4		
		ZO	L12-4R5		

*Also appears elsewhere

TABLE 2.5

Electrocutaneous Katakana Syllabary

CODE #4

A	R10	MA	L5 R10	DA	L1 R3-10
*I	R7	MI	L5 R7	(ZI)*DI	L1 R3-7
*U	L7	MU	L5-7	DU	L1-7R3
*E	L8	ME	L5-8	DE	L1-8R3
*O	L10	MO	L5-10	DO	L1-10R3
KA	R1-10	YA	L4 R10	BA	L1 R5-10
KI	R1-7	*I	R7	BI	L1 R5-7
KU	R1L7	YU	L4-7	BU	L1-7 R5
KE	R1L8	*E	L8	BE	L1-8 R5
KO	R1L10	YO	L4-10	BO	L1-10R5
SA	R2-10	LA	L3 R10	PA	R6-10
SI	R2-7	LI	L3 R7	PI	R6-7
SU	R2L7	LU	L3-7	PU	L7 R6
SE	R2L8	LE	L3-8	PE	L8 R6
SO	R2L10	LO	L3-10	PO	L10 R6
TA	R3-10	WA	L2 R10		
(CHI)TI		*I	R7	.	L 5
TU	R3L7	*U	L7	,	L 4
TE	R3L8	*E	L8	1	L 3
TO	R3L10	*O	L10	<	L 1
NA	R4-10	WN	L2		
NI	R4-7	GA	L1 R1-10		
NU	R4L7	GI	L1 R1-7		
NE	R4L8	GU	L1-7R1		
NO	R4L10	GE	L1-8R1		
HA	R5-10	GO	L1-10R1		
HI	R5-7	ZA	L1 R2-10		
HU	R5L7	(DI)*ZI	L1 R12-7		
HE	R5L8	(DU)*ZU	L1-7R2		
HO	R5L10	ZE	L1-8R2		

*Also appears elsewhere

Method

Subjects

Native Japanese, of both sexes, living in the Louisville area served as Ss in the code training experiment. Ss reported for training sessions in pairs. Each training session lasted two hours, and each S received $4.00 per session. Because of the scarcity of Ss, it was not possible to exercise any meaningful selectivity in choosing them. Consequently, both slow and fast learners were employed. However, an effort was made to distribute Ss in such a way that each group contained slow and fast learners. Five of the 7 Ss employed so far were females.

Apparatus

Two systems for applying patterned electrical stimuli were constructed. The first was an electromechanical system consisting of two sections, a signal delivery section and a control section. In the control section, seven relays were connected in a binary tree configuration. By utilizing all possible combinations of control relay closures, 128 different circuits could be selectively established. The seven control relays could be operated manually, or with an 8 hole tape reader. The signal delivery system consisted of 128 signal relays, each controlled by a particular combination of closures in the binary tree. Each signal relay, when closed, connected three independent stimulus sources to three terminals on a plugboard. The stimuli were finally distributed to the appropriate palm and fingertip locations by means of a plug inserted in the plugboard. The constitution of stimulus patterns, with respect to number and location, was determined by the manner in which the plug was wired. Thus, the desired code was selected by inserting the appropriately wired plug in the plugboard.

Each of the three stimulus courses consisted of an automobile ignition coil with a 1.5 volt battery connected to its low voltage terminals. One high voltage terminal of each coil was connected to the appropriate hot input terminal on the signal relay section. There was a common return path for the three coils to the other high voltage terminal. This return went through the normally open contacts of a relay which closed when any one of the signal relays closed, and opened again, by appropriate timing circuitry, a fraction of a second later. It was the pulse generated upon opening this relay that was used as the stimulus. The smaller pulse generated by closing this relay was suppressed by a diode in the return path.

The heads of stainless steel pan head screws, approximately one fourth inch in diameter were used as active electrodes. Ceramic clay handprints were made for each of the Ss. The electrodes were embedded in these handprints in such a way that when S placed his hands in his handprints, the electrodes made contact with the locations that had been selected for use in the experiment. Two German silver limb electrodes, one on each wrist, were used as passive electrodes.

S received his training in an Industrial Acoustics Chamber Model 400 and communicated with E outside the booth, by means of an ordinary intercommunication system. On the wall of the booth in front of S there was a chassis, with potentiometers mounted on it, one for each of the locations to be stimulated. These potentiometers were used by S to adjust stimulus intensity for comfort and for equal apparent intensity at all stimulated locations. In addition, there was a potentiometer, connected in the common return, that changed the stimulus intensity at all locations simultaneously.

The apparatus just described was used for most of the code training described in this report. However, experience with it revealed inherent difficulties that seriously limited its usefulness. Voltages at various points of the circuit were often quite high. Because many wires were in close proximity, there was eratic arcing which resulted in unwanted variability in stimulus intensity. Because the wiring scheme was very complex, such problems were difficult to isolate and correct. Furthermore, since the presentation of many signals required the simultaneous closure of six or eight relays, sluggish operation of several relays in the system could significantly retard the rate at which signals could be sent. Although this has not become a problem, it was anticipated that when Ss became more proficient in the reception of code, their communication rate might be limited by the pace of the apparatus. Finally, as a result of consultation with Dr. Robert Gibson at the University of Pittsburgh, a paid consultant on the project, a decision was made to change the character of the stimulus. The pulse resulting from the collapse of an inductive field rises to peak voltage almost instanteously and decays exponentially. Its duration above threshold is approximately one half msec. The shape and duration of this pulse necessitated the use of a rather high stimulus intensity, and this in turn resulted in occasional muscle jerks. In the apparatus described here, the polarity of this pulse was not changed on successive administrations. There was a possibility that some of the uncontrolled stimulus variability might be due to a failure to reverse stimulus polarity after each administration. The apparent solution to these problems was the use of alternating current for code signals. Alternating current would eliminate the possibility of polarization effects. A high enough frequency of alternation would result in conduction near the surface of the skin, and hence the problem with muscle jerks should disappear. Finally, the use of an ac stimulus would permit the adjustment of stimulus duration. Greater stimulus duration would permit weaker stimulus intensity which would, in turn, help relieve the problem of muscle jerks. For these reasons, a decision was made to construct another code sending system in which relays were replaced by solid state circuitry. A description of this apparatus follows.

The new system makes use of the transistorized logic modules manufactured by BRS Electronics. The system includes a photo cell tape reader, together with the logic required to step it at a rate that can be varied continuously. In addition, logic is provided to set up the tape reader as a block reader. The tape is read two lines or 16 holes at a time. Each of these holes controls a stimulus relay. When a block is read, the output is applied to relay drivers which energize the relays used in switching stimulus current. Each of these relays controls the stimulus current for one of the locations used in the code, and each code signal is presented by closing the appropriate combination of relays. Stimulus current is provided by an audio frequency oscillator. The output of this oscillator is amplified by a specially constructed amplifier with three independent output sections, one for each of the three stimulus locations that may be represented in a code signal. The amplifier outputs are coupled to the skin through input transformers with high impedance secondaries, in order to secure an approximate impedance match. As before, S receives training in a sound proof booth, and may adjust stimulus intensity for comfort and for equal apparent intensity at all stimulated locations by resort to an array of 200,000 ohm potentiometers on a chassis on the wall in front of him. Each potentiometer is connected in series with one of the stimulus electrodes and also serves the function of limiting fluctuation in stimulus current due to changes in S's skin impedance.

It will be recalled that common passive electrodes were used in the first code apparatus. Though the skin area contacted by these electrodes was quite large in relation to the skin area contacted by the active electrodes, stimulation was occasionally experienced either at the site of the passive electrodes, or at some point intermediate to the two electrode sites. To solve this problem, passive electrodes have been eliminated, and stimulus current is now delivered by means of an array of small, closely spaced electrodes. Electrodes are arranged in two vertical columns, with three electrodes per column. Electrode diameter is approximately one eighth of an inch, and the center-to-center spacing between adjacent electrodes is approximately five thirty seconds of an inch. The top and bottom electrodes in the left hand column and the middle electrode in the right hand column are connected together and to one side of the circuit, while the remaining electrodes are connected together and to the other side of the circuit.

This configuration of electrodes was chosen because it conforms reasonably to the fingertip, because it is small in extent, and because it provides a fairly homogenious distribution of current density over the site of stimulation. These electrode assemblies are mounted on handboards, and their positions on these boards can be adjusted in accordance with individual differences in hand size. When the handboards have been set up for a particular S, and when he has his hands properly placed on them, all of the electrodes make contact with his skin at the appropriate locations.

Procedure

During the initial phase of training, codes were taught to Ss by a paired-associates method. An attempt was made to present the learning task in such a way as to minimize the number of errors made during learning. The Katakana Chart was taught, a column at a time, and in the conventional order from right to left (see Table 2.1).

During the first, or familiarization stage, Ss were presented with the code signals to be associated with the first five characters in the Katakana Chart. On the first two trails, these characters were presented in the conventional order, (read down the right most column in Table 2.1) and the name of each signal was announced by E in advance of its presentation. S responded to each signal by repeating its name. Next, S received 10 trials in which the signals were cued by E as before, but in which the order of signals was randomly permuted from trial to trial.

In the learning stage, each of S's trials consisted of 10 random permutations of the five characters. Names of signals were not announced in advance by E, and S's naming errors were recorded. When S made an error, he was so informed, and given the signal again, together with its correct name. Trials were administered to S until criterion was reached. The criterion of mastery varied from S to S because of differences in S's ability. Some Ss received a criterion of two successive errorless trials without difficulty. It soon became apparent that if the same criterion were demanded of other Ss, a very large number of trials would have been required, and they would have become discouraged. It seemed wiser to relax the criterion somewhat for these Ss, and to allow them to advance to the next column of the syllabary without having demonstrated prolonged error free performance.

When a S completed his work on column 1 of the syllabary, the procedure was repeated, using the five characters in column 2. Following this, Ss were asked to identify a list of words constructed from the characters in columns 1 and 2. One time through this list was considered a trial. Trials were administered until Ss reached a satisfactory criterion of mastery.

Code learning proceeded from column to column in this manner. Each time a new column was mastered, S was given words to identify that were spelled with the characters in that, and all previously learned columns. It was felt that the introduction of the word identification task in this manner would accomplish two ends. First, it would constitute a review of previously learned code signals. Secondly, it would permit S the experience of interpreting meaningful sequences of signals, and thus afford him practice in the utilization of those cues based on the sequential probabilities for the occurance of characters in words.

Ss were trained in pairs during sessions that lasted approximately two hours. They received code instruction alternately, for periods of one half hour. Thus, during a two hour session, each S received one hour of actual code instruction. When one S was "off duty", he assisted E in recording the responses of the S "on duty". Since, in this arrangement, each S was continuously aware of his teammate's performance and could compare it with his own, there was a spirit of competition which probably improved motivation during training.

Results

In order to compare the four codes, Ss' responses have been entered in confusion matrices. In these matrices, the entries along the left hand margin refer to signals sent, while the entries along the top margin refer to signals received. Displaying the data in this way permits us to determine the percent of signals sent that were correctly identified, and to search for contingencies between stimulus location and error frequency. Tables 2.6 through 2.13 present confusion matrices for eight Ss. "I don't know" responses are entered in the columns headed with question marks. The bottom row in each matrix gives the percent of correct identification for each signal. The mean of these percentages can be regarded as an indication of overall accuracy on the first three columns of the syllabary for the S whose responses are recorded in the matrix. The mean of these mean percent correct values for each of the Ss working on a particular code is an overall mean percent of correct identifications for that code. The results of this analysis are displayed graphically in Figure 2.3. It can be seen that, in general, Ss trained on Codes 2 and 3 made about 10 percent more correct identifications than Ss trained on Codes 1 and 4.

By reference to the confusion matrices and to Figure 2.1, it is possible to determine the relative contributions of the various stimulus locations to the observed confusions. For example, in Code 1, S L. confused "I", "U", and "E" in column 1 of the syllabary. Referring to Table 2.2, we see that "I" is signalled by a stimulus at R10, "U" by a stimulus at R11, and "E" by a stimulus at R12. In column 2 of the syllabary, S L. confused "ki", "ku", and "ke" most frequently. "Ki" is signalled by simultaneous stimuli at R2 and R10, "ku" by stimuli at R2 and R11, and "ke" by stimuli at R2 and R12. In both these examples, the confusing signals involved stimulation at palmar locations.

In leaning Code 1, S H. confused "I" (R10) with "A" (R1), "se" (R3 and R12) with "so" (R3 and R6), and "ki" (R2 and R10) with "ku" (R2 and R1). Thus, her greatest difficulty was in discriminating R1 (right little fingertip) from R10 (base of right little finger). This discrimination has proved difficult for most Ss.

TABLE 2.6

Confusion Matrix for Subject L, Code 1

RECEIVED

		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	91	14	4	1												
	I	15	59	18	18												
N=110	U	6	8	74	21												1
	E	2	9	34	65												
	O				1	109											
	KA						80	2	5	3							
SENT	KI				1		14	53	14	7	1						
	KU		4				3	16	60	7							
N=90	KE		1				1	2	18	68							
	KO									1	89						
	SA											35	4	1			
	SI											4	25	2	7	2	
N=40	SU												1	26	13		
	SE												2	3	32	3	
	SO													1	1	38	
% Correct:		83	54	67	59	99	89	59	67	76	99	88	63	65	80	95	

TABLE 2.7

Confusion Matrix for Subject H, Code 1

RECEIVED

		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	78	22														
	I	13	84	3													
N=100	U		3	97													
	E				97	1											2
	O				1	99											
	KA						94	5		1							
SENT	KI						19	79	2	7							
	KU								98	2							
N=100	KE							3		96	1						
	KO						1				99						
	SA											18	1		1		
	SI												18		1	1	
N=20	SU													18		2	
	SE														16	4	
	SO															20	
% Correct:		78	84	97	97	99	94	79	98	96	99	90	90	90	80	100	

TABLE 2.8

Confusion Matrix for Subject Z, Code 2

RECEIVED

	SENT	A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	20															
	I		18		2												
N=20	U		4	15		1											
	E			1	19												
	O				5	15											
	KA						10										
N=10	KI							10									
	KU							1	9								
	KE									10							
	KO										10						
N=10	SA											10					
	SI												10				
	SU													10			
	SE														10		
	SO															10	
% Correct:		100	90	75	95	75	100	100	90	100	100	100	100	100	100	100	

TABLE 2.9

Confusion Matrix for Subject S, Code 2

RECEIVED

		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	10															
N=10	I		10														
	U			10													
	E				10												
	O					10											
	KA						10										
N=10	KI							10									
	KU								10								
	KE									10							
	KO										10						
	SA											10					
	SI												10				
N=10	SU													10			
	SE														10		
	SO															10	
% Correct:		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	

TABLE 2.10

Confusion Matrix for Subject S. C., Code 3

RECEIVED

		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	10															
	I		10														
N=10	U			10													
	E				10												
	O					10											
SENT	KA						30										
	KI							30									
N=30	KU								25	5							
	KE							1	4	25							
	KO							1	2	1	26						
	SA											10					
	SI												10				
N=10	SU													10			
	SE														10		
	SO															10	
% Correct:		100	100	100	100	100	100	100	83	83	87	100	100	100	100	100	

TABLE 2.11

Confusion Matrix for Subject M. C., Code 3

RECEIVED

SENT		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	75			1												4
	I	1	73														6
N=80	U			76													4
	E	1			75												4
	O					78											2
	KA						66	2									2
	KI							67									3
	KU								62								8
N=70	KE								2	68							
	KO										70						
	SA											77			2	1	
	SI											2	76	2			
N=80	SU													73	7		
	SE											1		2	77		
	SO														1	79	
% Correct:		94	91	95	94	98	94	96	89	97	100	96	95	91	96	99	

TABLE 2.12

Confusion Matrix for Subject Z, Code 4

RECEIVED

	SENT	A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	30															
	I		29			1											
N=30	U			23	7												
	E		2	9	18												1
	O					30											
	KA						29	1									
	KI						3	27									
N=30	KU							2	28								
	KE								5	24	1						
	KO							1			29						
	SA											18	2				
	SI											7	13				
N=20	SU													19	1		
	SE													3	16	1	
	SO															20	
% Correct:		100	93	77	60	100	97	90	93	80	97	90	65	95	80	100	

TABLE 2.13

Confusion Matrix for Subject S, Code 4

RECEIVED

		A	I	U	E	O	KA	KI	KU	KE	KO	SA	SI	SU	SE	SO	?
	A	30															
	I		29														1
N=30	U			24	6												
	E			3	27												
	O					30											
SENT	KA						56	4									
	KI						15	45									
N=60	KU						2		45	12	1						
	KE						1	1	9	49							
	KO							1	4	1	54						
	SA											17	2		1		
	SI											3	17				
N=20	SU													14	5	1	
	SE													3	16	1	
	SO											1		2	1	15	1
% Correct:		100	97	80	90	100	93	75	75	82	90	85	85	70	80	75	

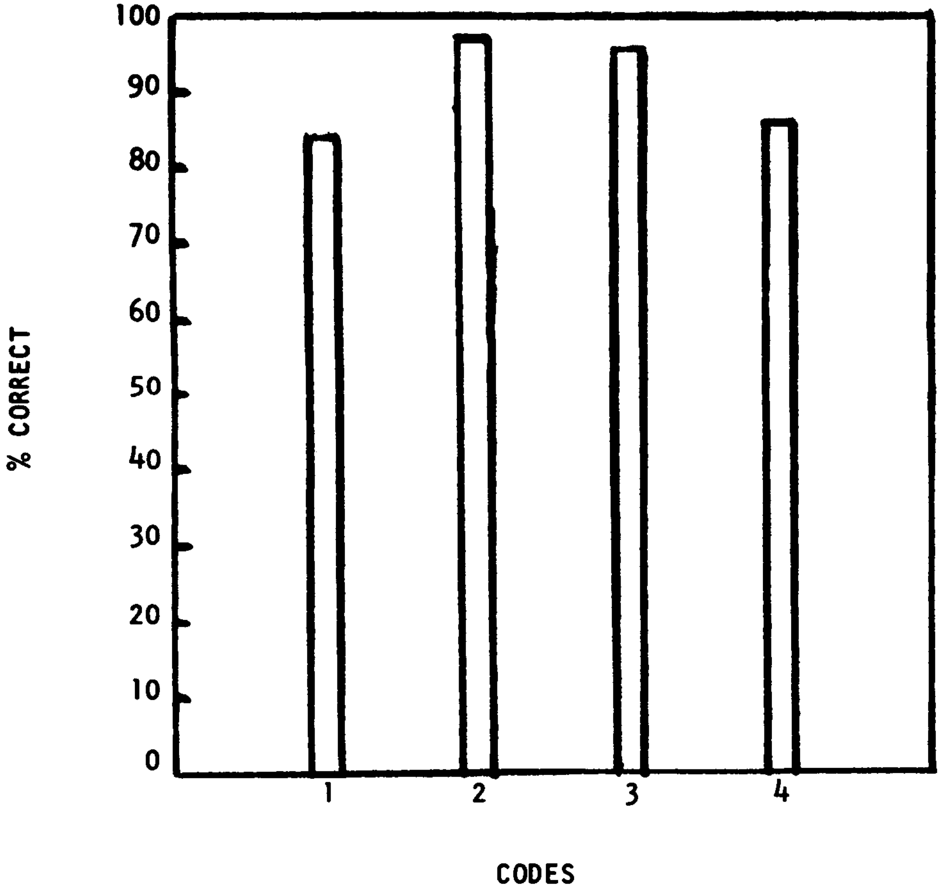

Figure 2.3 Mean percent correct identifications for the first three columns of the Katakana electrocutaneous codes.

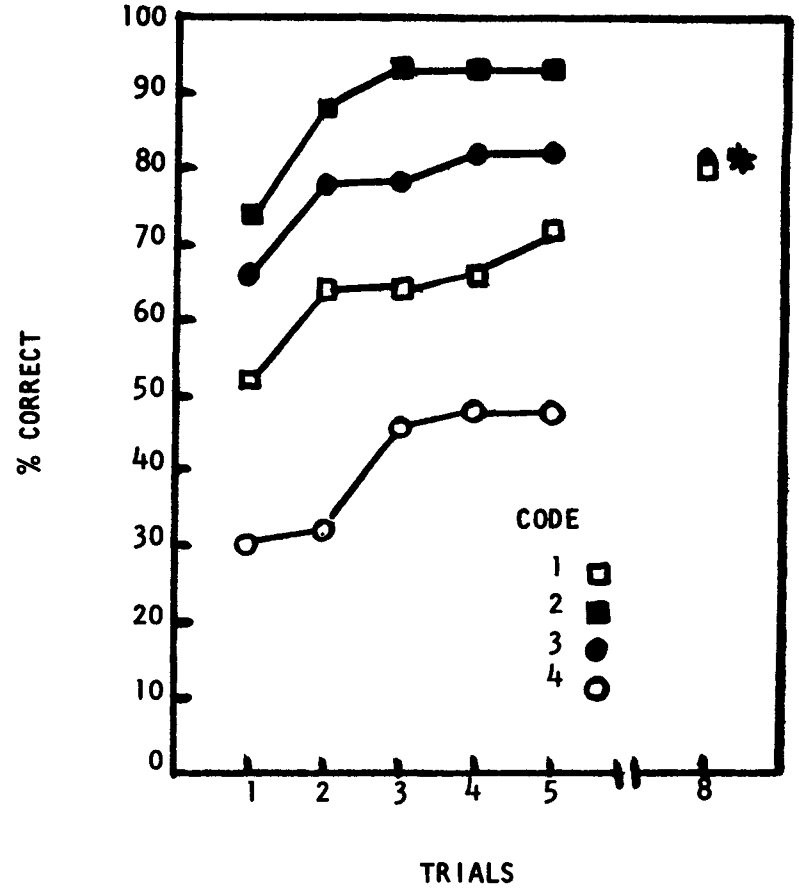

Figure 2.4 Learning curves for words formed by use of the first three columns of the Katakana electrocutaneous codes (N=50 words per trial). *see text

Figure 2.4 presents four learning curves, one for each code, that summarize the effects of practice on a list of 32 words formed from the characters in the first three columns of the Katakana Chart. In this figure, Trials are displayed on the abscissa, while the ordinate is scaled in terms of the percent of correctly identified words per trial. A mean percent of words correctly identified by the Ss learning a given code was determined for each trial and these means were used in plotting the four curves through Trial 5. The curves for the Ss learning Codes 1 and 3 have been extended beyond Trial 5 in order to convey a picture of the course of code acquisition typical of slow learners. Both of these Ss ceased to show improvement by the eighth trial. The performance of the slow learners had a depressing effect on the mean values used in plotting the curves in this figure. However, since there was a fast and a slow learner for each of the Codes 1, 2 and 3, and two average learners for Code 4, the impression of average performance conveyed by Figure 2.4 is reasonably reliable. Many lists of words have now been learned by our Ss, but the data just shown are typical and have been presented here for illustrative purposes.

Analysis of this sort has lead to the conclusion that signals involving palmar locations are frequently confused, while signals involving only fignertip locations are rarely confused. Codes 2 and 3, for instance, depend less heavily upon the use of palmar locations than the other two codes. As a consequence, performance on these codes has been significantly better.

Current Status

Training on the four original Codes has been discontinued. When it resumes, Ss will be taught a new "final" code, the construction of which has been guided by the experience gained with the previous codes. Only fingertip locations are to be used, and the stimulus will be an alternating current. Pilot studies now completed suggest that a stimulus of 400 cps with a duration of 25 msec. is quite suitable for our purposes. Ss will receive training on the "final" code until a point is reached at which additional training fails to yield significant improvement in performance. At this point, it will be possible to make judgments regarding the utility of a communication system that uses the skin as a channel of communication, electric current as the input to this channel, and syllables as code units.

Part III

Reaction Time to the Onset and Offset of Electrical Stimulation

In order to gain a better understanding of the nature of electrocutaneous stimulation, studies which are collateral to the electrocutaneous code project, and which deal with basic stimulus-response relations, are being conducted. Two basic aspects of a stimulus event are its onset (beginning) and its offset (ending). Stimulus onsets and offsets must be discriminable if code units are to be perceived. The studies reported hereafter were performed to determine the relative discriminability of the onsets and offsets of electrical stimuli, as indexed by reaction time, at various intensities, frequencies, and rise-decay times. Where appropriate, underlying neurophysiological functions have been suggested as explanations for our psychophysical data.

Experiment I: The Effects of Intensity

Woodrow (1915) found a faster reaction time (RT) to the onset of an alternating current than to its offset. He reported that, following the offset of his stimuli, sensations of "aftertingling" occurred. He suggested that these sensations may have interferred with the detection of offset, with longer RTs as a consequence. Because Woodrow's work was, by his own declaration, only cursory and crude, it was decided to investigate this pheomenon again, using the more sophisticated electronic instruments that have been developed since Woodrow's work. Also, it was decided to vary several stimulus paramaters in the belief that the consequences of such variation would have theoretical significance. In the first experiment, the stimulus intensity variable was examined.

Method

Subjects

The Ss were two male graduate students who were well practiced (three hours of training and over 450 reactions) in reacting to electrocutaneous stimuli of the sort used in the present study.

Apparatus & Procedure

The stimulus was a 70 cps sinusoidal electric current produced by a Hewlett-Packard audio frequency oscillator, Model 201CR. The output of the oscillator was connected through a Grayson-Stadler electronic switch, Model 829D, and a Daven attenuator, Type 7707, to the input of a 75 watt McIntosh amplifier, Model MC75. Use of the electronic switch permitted transientless switching at controlled rise and decay times. The attenuator permitted adjustment in stimulus intensity in steps of 1 db over a range of 20 db. An approximate impedance match between the 600 ohm output of the amplifier and S's skin impedance was secured with a UTC transformer, Type LS12. A 200-K-ohm resister was connected in series with S in order to limit fluctuations in stimulus current due to changes in S's impedance. A 100 ohm precision resistor was also connected in series with S and stimulus current was determined by dividing the voltage drop across this resistor, as measured by a Ballantine volt meter Model 200E, by 100.

S was seated in an IAC testing booth, Model 400. The stimulus was delivered to him by means of a stainless steel electrode, five eighths inches in diamater, centered on the volar surface of the distal phalange of the left index finger. The passive electrode was a stainless steel rectangle, $2\frac{1}{2} \times 3\frac{1}{2}''$, applied to the palm of the left hand.

To obtain a reaction from S, E set his controls and then signaled S that all was ready. Upon receipt of this signal, S held down a telegraph key with his right hand. When S felt that he was ready to react, he depressed a foot switch which operated a Hunter timer, Model 100B, connected in the external control circuit of the electronic switch. The relay closure occuring at the end of the time interval (foreperiod in this experiment) for which the Hunter timer was adjusted, presented the stimulus by switching the electronic switch and also started a Hunter Klockkounter. S's reaction, releasing the telegraph key, stopped the Klockkounter and his reaction time could then be read from its dials to the nearest msec.

The foreperiod was varied randomly from two to four seconds to prevent response syncronization by S. In the onset condition, electrical stimulation commenced at the end of the foreperiod and S reacted to its onset. In the offset condition, electrical stimulation was present during the foreperiod, and S reacted to its offset.

S reacted to the onset and offset of the stimuli at three different intensities. Thus, there were six experimental conditions. The intensities of the stimuli presented to the two Ss were adjusted slightly to take into account individual differences in absolute threshold and the ability to discriminate. For S S. A., the intensities were 440, 560 and 700 μA. For S H. T. they were 480, 570 and 720 μA. There were two experimental sessions and, during each session, twenty-five RTs were recorded for each of the experimental conditions. Thus, there were 50 observations of RT for each intensity X stimulus event combination. The 25 stimuli fulfilling each condition of the experiment were presented in blocks of five. There were thirty of these blocks in each experimental session, and they were presented to the two Ss in counter balanced sequences to control for the possibility of an effect due to order.

Results

The median RT was determined for each block of five RTs. Then, the ten medians for each experimental condition were averaged to obtain mean RTs. The mean RTs for the six experimental conditions and their corresponding standard deviations are shown in Table 3.1. The relation between intensity and mean RT is displayed graphically in Figure 3.1, with intensity in μA on the abscissa, and mean RT in msec. on the ordinate. It is apparent from this figure that offset RTs are, in all cases, longer than onset RTs. Both offset and onset RTs increase as intensity decreases. The difference between offset and onset RTs is greatest at the lowest intensity, but does not appear to change much from the middle to the strongest intensity. Visual inspection suggests that, as intensity is decreased, the rate of increase in RT for offset is greater than for onset. This is most evident for S S. Z.

TABLE 3.1

Means and Standard Deviations of the Reaction Times for Two Subjects to the Onset and Offset of A C. Electrocutaneous Stimuli at Three Levels of Intensity (see text for intensity in μA).

Ss	Score	Intensity					
		Low		Medium		High	
		Onset	Offset	Onset	Offset	Onset	Offset
S.Z.	Mean	214	352	171	237	162	227
	S.D.	56	133	26	33	14	23
H.T.	Mean	347	476	257	297	214	254
	S.D.	63	103	27	47	29	18

TABLE 3.2

Means and Standard Deviations of the Reaction Times for Two Subjects to the Onset and Offset of A. C. Electrocutaneous Stimuli at Three Frequencies (cps.).

Ss	Score	Frequency (cps.)					
		70		270		500	
		Onset	Offset	Onset	Offset	Onset	Offset
S.Z.	Mean	162	226	159	223	187	332
	S.D.	23	16	21	18	23	15
H.T.	Mean	240	312	227	256	286	320
	S D.	12	14	16	14	22	51

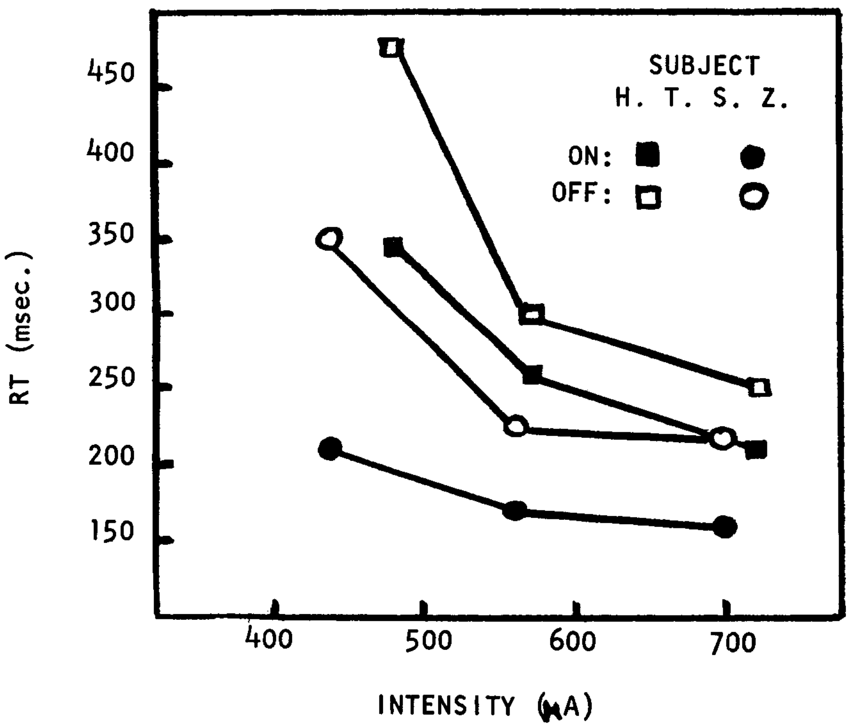

Figure 3.1 Mean reaction times (RT) for two subjects to onset and offset of electrocutaneous stimuli as a function of intensity in micro-amperes (μA).

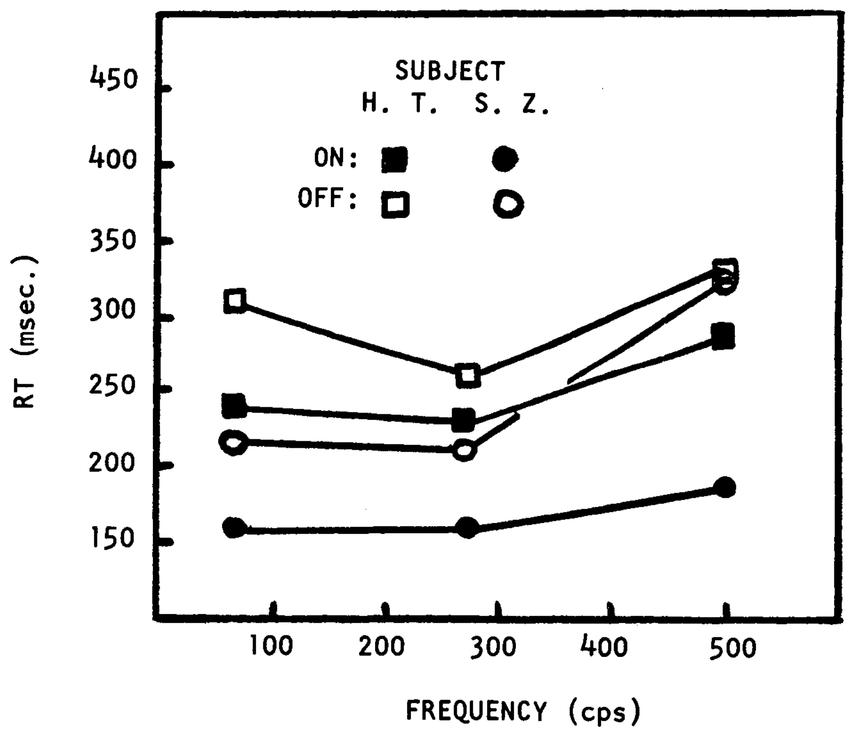

Figure 3.2 Mean RTs for two subjects to onset and offset electrocutaneous stimuli as a function of frequency (cps) of alternating current.

The differences shown in Figure 3.1 were tested for significance by the Wilcoxin matched-pairs signed ranks test (Siegel, 1956, pp. 75-83), using the 10 median RTs obtained under each of the six conditions for each S. In all cases, the obtained p was less than 0.01. The intensity variable was tested for significance by means of a Friedman two-way analysis of variance (Siegel, 1956, pp. 166-172), using the means presented in Table 3.1. The changes in RT to onsets and offsets as a function of intensity were significant at the 0.005 level.

Discussion

The present results confirm Woodrow's finding that RT is faster to the onset than to the offset of electrical stimulation. Woodrow suggested, as an explanation of his results, masking caused by the aftertingling that followed his stimuli. In the present study, Ss reported no aftertingling. They did report a tendency for the stimulus to "adapt out" with continued stimulation. This was most apparent at the weaker intensities. Thus, the subjective intensity of the stimulus was less at the offset than at the onset of stimulation, a fact that is consistent with the finding of longer RTs to stimulus offsets than onsets.

Experiment II: The Effects of Frequency

In this experiment, intensity was held at 565 μA while the frequency of the ac stimulus was varied. The frequencies at which tests were conducted were 70, 270, and 500 cps. The Ss apparatus and procedure were the same as in Experiment I.

Results and Discussion

Again, the median RT for each block of five trials was computed, and the means and standard deviations of these medians for each frequency X onset-offset combination were determined, as shown in Table 3.2. In order to make the outcome of the experiment more evident, the influence of change in stimulus frequency on onset and offset RT is shown graphically in Figure 3.2. As shown in this figure, offset RTs were, in all cases, longer than onset RTs. These differences were tested for significance and were found, with one exception, to be significant at the .005 level. The exceptional case was that of S H. T. at 500 cps, where the difference was significant at the .05 level. A relationship between frequency and RT is suggested, though not clearly indicated, in Figure 3.2. Sensitivity, as indexed by RT, was apparently greatest at 270 cps, and least at 500 cps. Examination of the records of individual Ss (refer to Table 3.2) is instructive in this connection. The relationship is strongly suggested by the performance of S H. T., but, for S S. Z. there appears to be only a slight relationship with respect to offset RTs, and no relationship at all with respect to onset RTs. In spite of this somewhat confused picture, a Friedman analysis of variance indicated overall significance for the frequency variable.

Experiment III: Reaction Time As a Function of the Rise and Decay Time of the Electrical Stimulus

In his discussion of the adaptation of nerves and sense organs, Adrian (1928) offered evidence for a rapid increase in the frequency of neural impulses at the onset of stimulation, followed by a gradual decline in the frequency of impulses with continued stimulation. At the psychophysical level, Travis & Griffith (1936) have reported a rapid initial adaptation to ac stimulation, followed by a period of slower adaptation in which the intensity of sensation gradually diminishes. Findings such as these suggest an explanation for our observation of longer RTs to the offset than to the onset of electrical stimulation. At the onset of an ac stimulus, there is a sharp rise in the frequency of neural impulses. However, with continued stimulation, the firing rate decreases due to adaptation so that the change in neural activity is less at the offset of the stimulus than at its onset. If, in the case under consideration, a change in sensory nerve activity is the occasion for a reaction, the change in sensory nerve activity at the offset of stimulation may not be as easily detected as the relatively larger change in activity at the onset of stimulation, with the result that more time is required to react to it. If this is the case, presentation and termination of a stimulus in such a way as to reduce the difference between onset and offset activity should have the effect of reducing the difference between the time required to react to the onset of stimulation and the time required to react to its offset. Since use of an ac stimulus with a very slow rise and decay time should avoid the rapid initial increase in nerve impulses, it may be possible to make the required test by a systematic variation of stimulus rise and decay time. Accordingly, a 3 factor experiment was performed in which stimulus rise time, stimulus decay time, and stimulus intensity were varied.

Method

Subjects

Three male students served as Ss. Prior to the experiment, each student made at least 1,000 practice reactions to electrical stimuli.

Apparatus and Procedure

The apparatus was the same as that employed in Experiments I and II. Stimulus rise-decay time was varied by means of the electronic switch. The stimuli to be used in the experiment were displayed on a Tektronix storage oscilloscope, Model 549, and found to be sigmoidal in shape.

Stimuli with rise-decay times of .5, 5, 26, 140 and 340 msec. were employed. They were presented at five intensities: 2, 4, 6, 8, and 10 db above S's threshold. These values were chosen because they span an intensity range from near threshold to strong. The threshold for each S was determined, prior to the experiment, by a simplified method of limits in which only stimulation of increasing intensity was used. Because of occasional changes in S's sensitivity during the 10 experimental sessions, it was necessary to increase the weakest intensity at times and so the intensities reported below are means. However, adjustments in intensity were never larger than 20μA. The stimulus intensities experienced by the three Ss were: E. P. = 338, 400, 500, 640, and 800μA; L. M. = 426, 550, 693, 881 and 1,033μA; R. H. = 340, 400, 520, 700 and 900μA.

The program for a single experimental session consisted of the determination of four onset RTs for one intensity X rise time combination, repeated by four off-set RTs for this stimulus combination. This procedure was followed for all 25 intensity X rise-decay combinations. There were 10 experimental sessions in all, and hence forty RTs were obtained for each stimulus combination. In half of the experimental sessions, onset RTs were collected first. In the remaining half, this order was reversed. Also, the order in which the 25 intensity X rise-decay time combinations were administered was varied from session to session. These measures were taken to control for the possibility of order effects.

Results

Table 3.3 shows the means and standard deviations of RT for each S under each experimental condition. Figure 3.3 shows the relationship between rise and decay time, plotted on the abscissa in msec., and RT, plotted on the ordinate in msec., at five levels of intensity for the three Ss. With the exception of the offset RTs to the stimuli of weakest intensity, there appears to be a linear increase in RT as both rise time and decay time increase. With respect to onset RTs, the slope of the curve describing this relationship appears to become slightly less as the level of intensity increases. The slopes of the offset curves do not change as the level of stimulus intensity changes.

At the weakest stimulus intensity employed, there was an exponential increase in offset RT as decay time increased. This relationship was evident in the performance of two of the three Ss. Data collected two weeks after the conclusion of the experiment revealed the relationship for the third S as well.

TABLE 3.3

Means and standard deviations for each intensity, rise-decay time, and onset-offset combination for each subject.

Subject	Intensity μA		Rise-Decay Time (msec.) 0.5 On	0.5 Off	5.0 On	5.0 Off	25 On	25 Off	140 On	140 Off	340 On	340 Off
L.M.	426	Mean	295	534	325	527	370	674	497	720	922	866
		S.D.	72	141	91	208	142	275	86	193	105	186
	550	Mean	179	318	210	343	243	344	441	486	821	658
		S.D.	26	72	46	63	26	56	61	104	50	75
	693	Mean	165	242	180	249	232	278	401	375	744	590
		S.D.	14	33	14	34	26	31	31	35	66	82
	881	Mean	159	220	177	229	222	247	383	352	718	502
		S.D.	14	22	16	32	20	25	34	42	35	63
	1133	Mean	156	209	167	210	209	233	380	322	683	585
		S.D.	12	27	16	16	10	24	37	14	30	46
E.P.	338	Mean	337	582	345	598	403	678	587	819	985	821
		S.D.	143	190	95	222	83	257	99	278	98	217
	400	Mean	283	521	302	536	347	476	555	583	854	781
		S.D.	61	195	66	165	69	155	63	195	138	211
	500	Mean	242	341	223	340	279	353	491	477	850	694
		S.D	82	94	44	118	52	73	60	95	41	116
	640	Mean	174	240	195	251	249	269	431	387	755	583
		S.D.	24	28	40	37	29	38	29	48	90	66
	800	Mean	166	213	180	219	233	242	401	336	735	529
		S.D.	18	25	20	19	23	27	24	27	42	44
R.H.	340	Mean	301	360	296	481	350	428	524	504	907	779
		S.D.	102	100	67	276	73	131	68	116	86	127
	400	Mean	227	274	205	310	267	304	476	487	823	647
		S.D.	57	65	73	86	70	58	47	109	61	83
	520	Mean	183	218	179	216	226	242	418	363	768	596
		S.D.	39	25	32	29	37	21	41	34	59	103
	700	Mean	157	191	173	204	221	228	383	325	703	559
		S.D.	30	15	24	16	27	32	24	21	37	87
	900	Mean	159	188	159	190	208	219	368	315	689	505
		S.D.	25	22	17	17	27	16	21	20	37	35

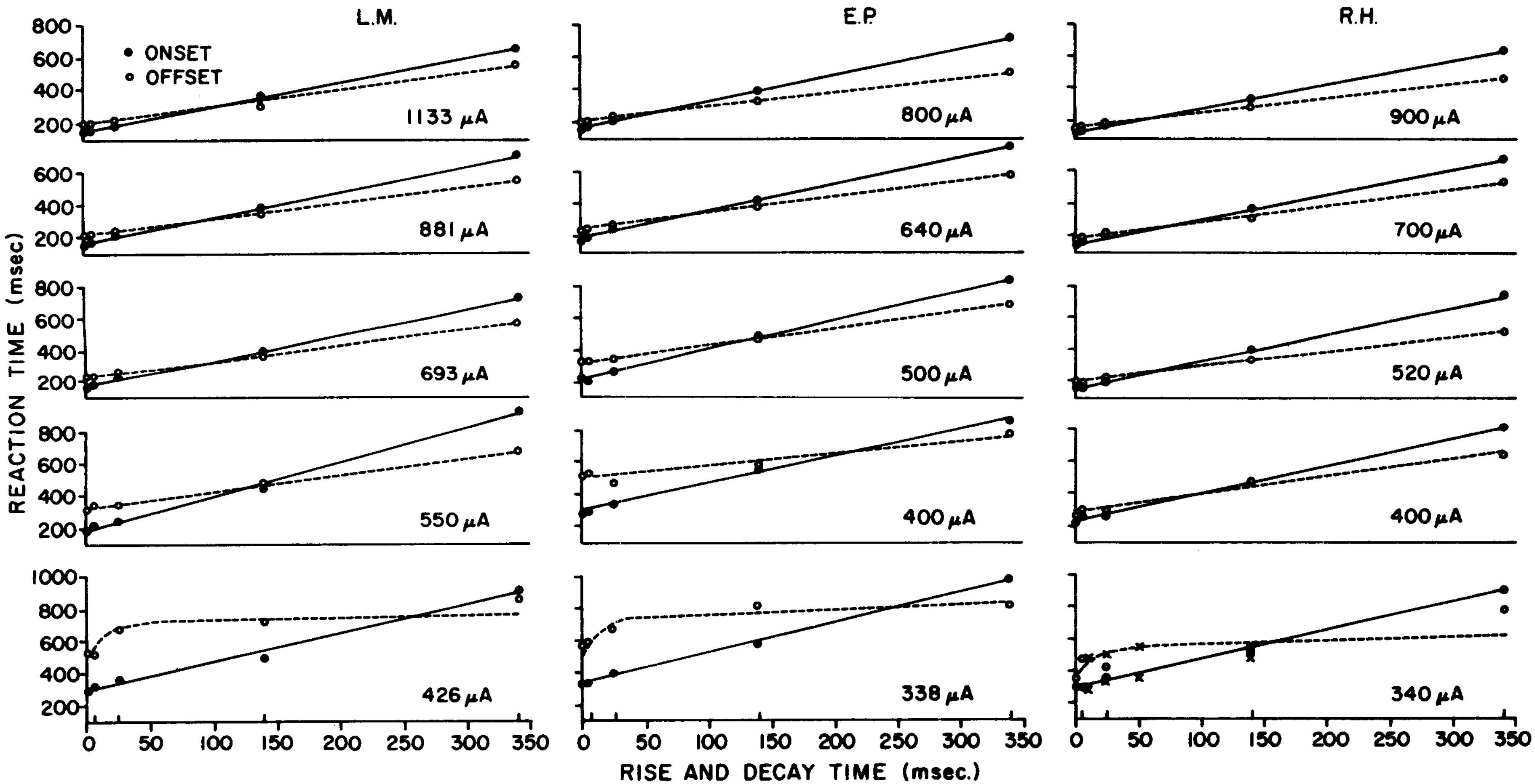

Figure 3.3 Mean reaction times for three subjects to onset and offset electrocutaneous stimuli of five rise and decay times and five levels of intensity.

A finding of primary interest was the reversal in the relative positions of the onset and offset RT curves as rise time and decay time increased. By inspection of Figure 3.3, the point of intersection for the onset and offset curves at a given intensity level can be ascertained. By dropping a line from this point to the abscissa, one can read the ramp time that results in equal onset and offset RTs. The way in which on=off ramp time depends upon stimulus intensity is shown in Figure 3.4. In this figure, the on=off ramp times for each S are shown by the dotted curves. The solid curve is the mean on=off ramp time for the three Ss and is plotted against mean intensity levels on the abscissa. The on=off ramp time decreases with increased intensity.

Discussion

The exponential offset curves obtained with the stimuli of weakest intensity are similar to the accommodation curves found by Kugelberg (1944) with rheobase measures and stimuli that rose to full strength at an exponential rate. We have found higher thresholds for offset stimuli than for onset stimuli. Thus, to be sure that all stimuli would be above threshold, stimulus intensities were adjusted in terms of offset rather than onset thresholds.

The finding that onset and offset RTs passed through a point of equality as the rate of change in energy at the onset or offset of the stimulus (ramp time) is increased, is consistent with an adaptation hypothesis. At longer rise times, the initial burst of impulses associated with fast rise times is avoided and hence the change in the level of neural activity resulting from the onset of the stimulus becomes more similar to the change that takes place at its offset. According to this reasoning, on=off ramp time for a given stimulus intensity is reached when the change in the level of neural activity at the onset of the stimulus is so similar to the change in the level at its offset that the two events become equally discriminable.

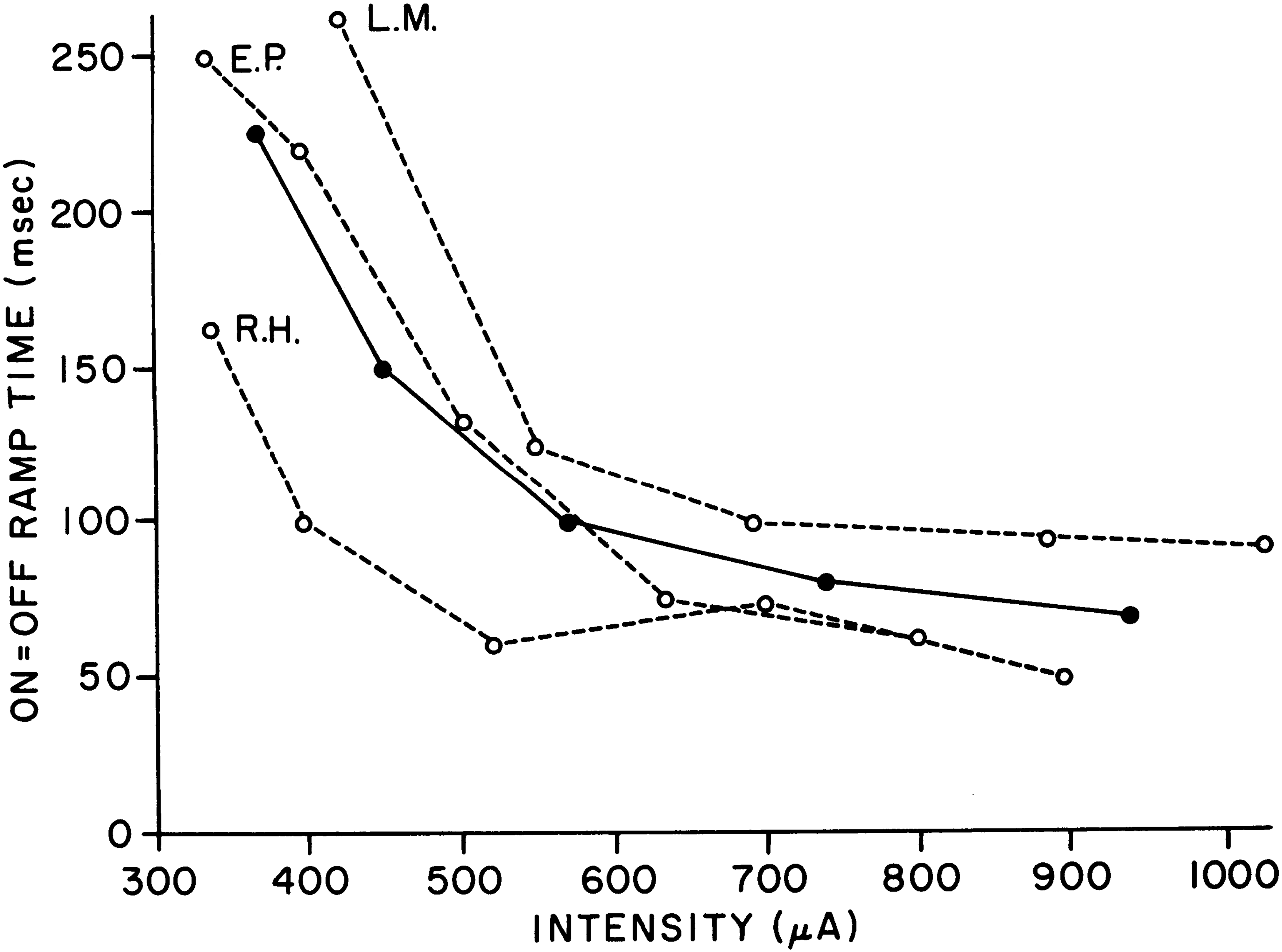

Figure 3.4 Rise and decay times (on=off ramp time) which produce equal onset and offset RTs.

The finding that offset RTs become longer than onset RTs at longer stimulus ramp times may be due to rapid accommodation of nerves to stimuli with long rise times which would raise the threshold for the detection of the onset of stimulation. Whether or not this is the case may be determinable by surface recording of compound peripheral nerve action potentials.

On=off ramp time may prove to be a useful index in psychophysical and electrophysiological studies involving electrocutaneous stimulation. For instance, if the increase in both onset and offset RTs associated with long stimulus ramp times is due to the accommodation of rapidly conducting fibers, then it ought to be possible to demonstrate the on=off ramp effect by ischemia, which has been shown to produce a decrease in the latency and amplitude of nerve action potentials evoked by stimulation of the ulnar nerve in man (Uttal, 1964).

Part IV

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